Force and position control of a hydraulic press

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Abstract: The article reports on the design and control of a 50-kN hydraulic press that was made for educational purposes as well as for an experimental verification of control algorithms. The press contains a servo-solenoid pressure-control valve for regulating the pressure in the cylinder chamber and thus the force of the hydraulic press. The press is equipped with a pressure sensor installed in the cylinder chamber for indirectly measuring the pressing force. On the press it is also possible to measure the position of the upper plate by using a micro-pulse linear transducer, which creates a precondition for the realization of a hybrid force/position-control algorithm. The control algorithms and monitoring process are implemented on a real-time hardware board. They are programmed in the Matlab/Simulink program using the Real-Time Workshop tool for generating the C code and building an executive program. The article also shows an industrial solution for hydraulic press control using a programmable logic controller (PLC) as a control device. Based on the experimental results, it can be concluded that electrically actuated control components supported by the appropriate computer programs make it possible to improve the characteristics of the hydraulic systems required in modern industrial plants.

Keywords: hydraulic press, force and position control, servo valve

1 Introduction

Modern industry is looking for flexible solutions that will be able to provide some new characteristics of hydraulic systems, such as the ability of controlled motion, the possibility for continuous control of the required values, simple data transfer and signal processing, the possibility of monitoring and process visualization, etc. The rapid developments in microelectronics in recent years have reduced the cost of computer equipment to a level acceptable for industrial applications, which has enabled the implementation of sophisticated control strategies in practice. Therefore, modern hydraulic systems have evolved towards electronics and microprocessor-controlled electro-hydraulic components in order to achieve new control possibilities [1]. Normally, due to its complexity, almost every advanced controller must be implemented on a digital computer. Such control systems that have electrically actuated valves can respond to the complex demands posed by today's technology.

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Presses are one of the most commonly used machine tools in industry for the forming of different materials. In the past, for the pressing tasks in industry, mechanical presses were more frequently used, but nowadays hydraulic presses take precedence due to their numerous advantages, such as:

- full force through the stroke,
- moving parts that operate with good lubrication,
- force that can be programmed,
- stroke that can be fully adjustable, which contributes to the flexibility of application,
- safety features that can be programmed and incorporated into the control algorithms,
- can be made for very large force capacities.

On the other hand, hydraulic presses are generally slower than mechanical presses [2]; however, this disadvantage is being overcome with the development of new valves with higher flow capacities, smaller response times and improved control capabilities. In these kinds of applications, the ability of force-control systems to follow-up varying reference signals is often required for the proper operation of the technological process. In addition, the task of the position control of the hydraulic actuator is also very important. Therefore, a new quality and significant improvement in the functioning of the press can be obtained with a simultaneous realization of position feedback, which is actually a hybrid control algorithm [3-5]. The hybrid force/position controller structure allows independent gains to be used for both the position and the force-control task, allowing the different dynamics of each to be adjusted. This paper describes the construction of a hydraulic press and the implementation of a control algorithm for its force and position control. The article also provides an example of hydraulic press control using a programmable logic controller (PLC) as a control device, which could be applied in practice.

2 Modelling and control

The mathematical model of the hydraulic system is obtained, first, from the model of the hydraulic valve dynamics, then by applying the flow continuity through the orifice, then by analyzing the pressure behaviour in the cylinder chambers, and, finally, by applying Newton's second law to the actuator motion. In this application a pressure-control valve was chosen because the emphasis is on the regulation of pressure, which is actually equivalent to the pressing force.

The transfer function between the spool-valve position $y_v(s)$ and the input voltage $u(s)$ is typically a second-order term:

$$\frac{y_{\mathrm{v}}(s)}{u(s)} = \frac{k_{\mathrm{v}}}{(1/\omega_{\mathrm{v}}^2)s^2 + (2\zeta_{\mathrm{v}}/\omega_{\mathrm{v}})s + 1} \tag{1}$$

where k_v is the proportional valve gain, ω_v is the natural frequency and ζ_v is the damping ratio.

The relationship between the spool-valve displacement, y_v, and the load flow, Q_L, assuming turbulent flow through an orifice can be given as:

$$Q_{\mathrm{L}} = K_{\mathrm{q}}\, y_{\mathrm{v}} \sqrt{p_{\mathrm{s}} - \mathrm{sgn}(p_{\mathrm{L}})} \approx K_{\mathrm{q}}\, y_{\mathrm{v}} - K_{\mathrm{c}}\, p_{\mathrm{L}} \tag{2}$$

where p_s is the supply pressure, $p_L=p_1-p_2$ is the load pressure and the coefficients K_q and K_c represent the flow gain and the flow-pressure coefficient, respectively.

There are three effects that contribute to the required flow rate Q_L, which are contributions due to the volume change, Q_V, due to the compression of the oil in the piston chamber, Q_c, and due to the leakage around the piston Q_1. It is assumed that these effects are additive, so we may use this consideration to write the following expression:

$$Q_{\mathrm{L}} = Q_{\mathrm{V}} + Q_{\mathrm{c}} + Q_{\mathrm{l}} = A_{\mathrm{p}} \frac{\mathrm{d}\,x_{\mathrm{p}}}{\mathrm{d}\,t} + \frac{V_{\mathrm{t}}}{4\beta} \frac{\mathrm{d}\,p_{\mathrm{L}}}{\mathrm{d}\,t} + K_{\mathrm{tc}}\, p_{\mathrm{L}} \tag{3}$$

where x_p is the position of the actuator, A_p is the average cross-sectional area of the piston, V_t is the total volume of fluid under compression in both chambers, β is the bulk modulus of the operating oil and K_{tc} is the total leakage coefficient of the piston, which includes the internal and external leakage coefficient.

The force balance equation for the cylinder is given by:

$$A_{\mathrm{p}}\, p_{\mathrm{L}} = m\,\ddot{x}_{\mathrm{p}} + b\,\dot{x}_{\mathrm{p}} + k_{\mathrm{s}}\, x_{\mathrm{p}} \tag{4}$$

where m is the effective system mass, b is the coefficient of viscous friction and k_s is the elastic load stiffness.

Using equations (1)-(4) a block-diagram of the process can be constructed. The control strategy, referred to as hybrid force/position control, is shown in Figure 1. With this control technique the errors in the force and position control loops are controlled by two independent controllers. The outputs from the force and position controllers are summed, giving a control signal that is sent to the servo valve to satisfy both the force and position reference commands.

Using block-diagram rules, the overall transfer functions of the process are obtained as follows [6]:

$$\frac{x_{\mathrm{p}}(s)}{u(s)} = \frac{k_{\mathrm{v}}}{\frac{1}{\omega_{\mathrm{v}}^2}s^2 + \frac{2\zeta_{\mathrm{v}}}{\omega_{\mathrm{v}}}s + 1} \cdot \frac{K_{\mathrm{q}}/A_{\mathrm{p}}}{\frac{m\,V_{\mathrm{t}}}{4\beta A_{\mathrm{p}}^2}s^3 + \left(\frac{b V_{\mathrm{t}}}{4\beta A_{\mathrm{p}}^2} + \frac{K_{\mathrm{ce}}\, m}{A_{\mathrm{p}}^2}\right)s^2 + \left(1 + \frac{b\,K_{\mathrm{ce}}}{A_{\mathrm{p}}^2} + \frac{V_{\mathrm{t}}\, k_{\mathrm{s}}}{A_{\mathrm{p}}^2}\right)s + \frac{K_{\mathrm{ce}}\, k_{\mathrm{s}}}{A_{\mathrm{p}}^2}} \tag{5}$$

$$\frac{F(s)}{u(s)} = \frac{k_{\mathrm{v}}}{\frac{1}{\omega_{\mathrm{v}}^2}s^2 + \frac{2\zeta_{\mathrm{v}}}{\omega_{\mathrm{v}}}s + 1} \cdot \frac{(K_{\mathrm{q}}/A_{\mathrm{p}})(m\,s^2 + b\,s + k_{\mathrm{s}})}{\frac{m\,V_{\mathrm{t}}}{4\beta A_{\mathrm{p}}^2}s^3 + \left(\frac{b V_{\mathrm{t}}}{4\beta A_{\mathrm{p}}^2} + \frac{K_{\mathrm{ce}}\, m}{A_{\mathrm{p}}^2}\right)s^2 + \left(1 + \frac{b\,K_{\mathrm{ce}}}{A_{\mathrm{p}}^2} + \frac{V_{\mathrm{t}}\, k_{\mathrm{s}}}{A_{\mathrm{p}}^2}\right)s + \frac{K_{\mathrm{ce}}\, k_{\mathrm{s}}}{A_{\mathrm{p}}^2}} \tag{6}$$

where $K_{\mathrm{ce}} = K_{\mathrm{c}} + K_{\mathrm{tc}}$ is the total flow-pressure coefficient.

The control concept using a PID controller with an anti-windup algorithm for the press force control and a fixed-gain PD controller for the press-position control is implemented. Eventual conflicts between the two controllers are managed by means of two gains, C_f and C_p, that can be used to determine the priority of the regulation and the contribution of each signal in the total control signal on the valve.

3 Experimental test setup

A schematic diagram and a photo

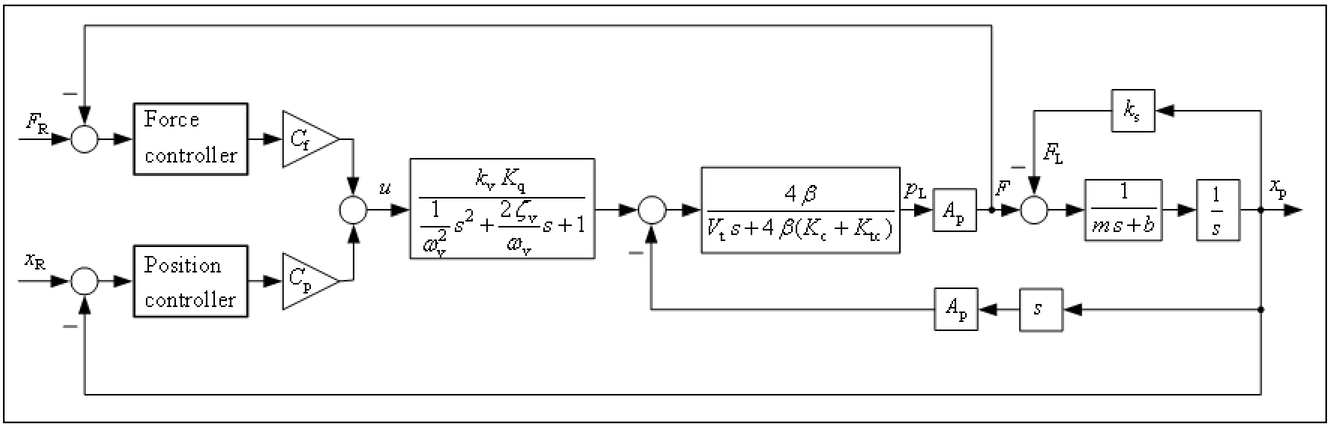

Figure 1. *Hybrid force/position control system*

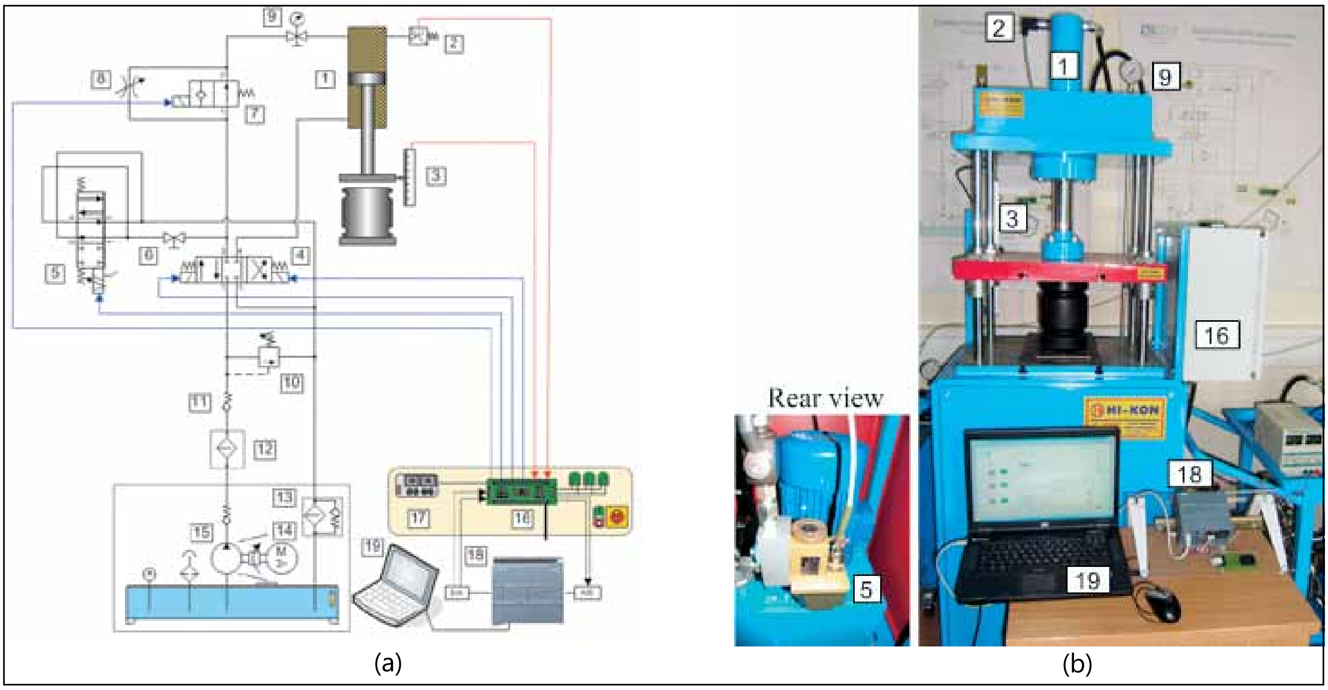

Figure 2. *Hydraulic press, a) schematic diagram, b) photo; 1–Cylinder, 2–Pressure sensor, 3–Micropulse linear transducer, 4–Solenoid 4/3 valve, 5–Servo valve, 6–Shut-off valve, 7–Solenoid 2/2 valve, 8–Throttling valve, 9–Manometer, 10–System pressure relief valve, 11–Ball check valve, 12–Pressure filter, 13–Return flow filter, 14–Three-phase electric motor, 15–Hydraulic pump, 16–Electronic interface, 17–Electric rectifier, 18–PLC SIMATIC S7-1200, 19–Control computer*

of the hydraulic press for control of the force and position are shown in Figure 2. The hydraulic cylinder (1) that is used to actuate the press is a double-acting 300-mm-stroke cylinder with an 80-mm bore and a 60-mm diameter rod. The control of the press force is accomplished using an electro-hydraulic servo valve (5) designed for bypass operation, manufactured by Schneider, model HVM 025-005-1200-0, with a box-chopper amplifier and ±10-V analogue input signal. The maximum pressure in the system is limited by a pressure relief valve (10) and the servo valve actually reduces the pressure in the system pressure line and the cylinder chamber. The servo valve is installed in a bypass line, and with respect to the control signal enables the oil flow to the tank, maintaining the pressure in the cylinder chamber at a desired value. The hydraulic force applied to a rubber bumper is indirectly measured by a pressure transducer (2), (Siemens type 7MF1564), with a measuring range of 0 to 250 bar and an output signal of 0 to 10 V, which is installed in the cylinder chamber. In this system it is also possible to measure the displacement of the press by using a micro-pulse linear transducer (3), manufactured by Balluff, type BTL5-A11-M0300-P-S32, with an output voltage of 0 to 10 V and a resolution of $\pm 2\mu m$. With the installation of the displacement sensor in the system, the preconditions for the realization of hybrid force/position-control algorithms are obtained. If the shut-off valve (6) is closed then the servo valve is turned off, and then it can be shown the action of a press whose motion is controlled using a classical solenoid 4/3 valve (4). Also, if the solenoid 2/2 valve (7) is closed, the oil flow is directed to a throttling valve (8) and this changes the cylinder speed. Since the servo valve is installed in the system, particular attention should be given to ensure the cleanliness of the oil, so a high-pressure filter (12) and a return flow filter (13) are set in the hydraulic circuit. The hydraulic power is provided by a hydraulic gear pump (15), model KV-1P from ViVoil, with a volumetric displacement of the pump of 2.6 cm3/rev and a maximum nominal pressure of 25 MPa. The oil pump is driven by a three-phase electrical motor (14), 2.2 kW at 980 rpm.

The data acquisition in the system is handled by a National Instruments DAQCard-6024E (for PCMCIA), which offers both a 12-bit analogue input and an analogue output. The control algorithms were developed in the Matlab/Simulink environment, supported by Real-Time Workshop (RTW) program for generating the C code and building a real-time application. This control technique allows for continuous monitoring of the process variables, data acquisition and software solution for real-time control. The command voltage to the servo valve is sent via an analogue output and to the solenoid valves it is sent via digital outputs on the data-acquisition board.

An industrial solution of the hydraulic press control is realized by using a programmable logic controller SIMATIC S7-1200, manufactured by Siemens (18). The control program was built using SIMATIC WinCC flexible software for programming the controller and configuring the HMI panel.

The considered system is actually one of three experimental electro--hydraulic systems that have been

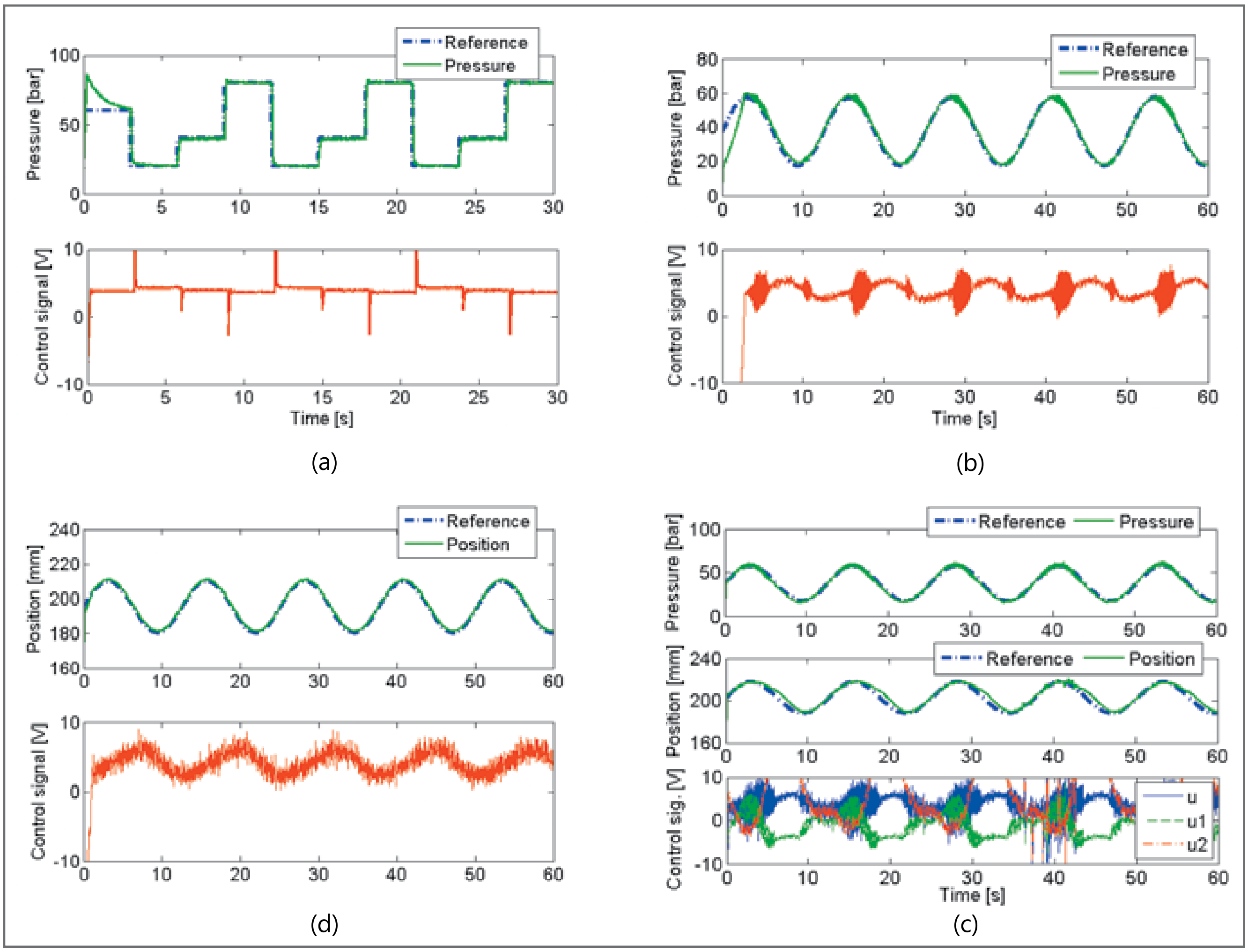

Figure 3. *Experimental results for hydraulic press control: a) pressure response for the step-reference signal, b) pressure response for the sinusoidal reference signal, c) position response for the sinusoidal reference signal, d) hybrid force/position control for the sinusoidal reference signal*

made in the Laboratory for Automation and Robotics at the University of Zagreb's Faculty of Mechanical Engineering and Naval Architecture. The modules are used for research purposes in the field of hydraulic systems control, as well as for training students [7-10]. The other two test systems are: the module for translational motion control and the module for rotational motion control. These modules have the characteristics of general electro-hydraulic systems, which are commonly used in industrial plants.

4 Experimental results

Experiments were first made for the regulation of the force achieved with the control of the cylinder pressure. To realize the control loop a pressure transducer installed in the cylinder chamber is used. The major drawback of this measuring method is that the friction force of the hydraulic actuator remains outside the control loop. Using pressure feedback in the control algorithm allows us to control the actuator force output. Figure 3a) shows the pressure response for a square-wave reference signal and the servo-valve control signal. It can be seen that the control system follows the reference trajectory with a small error and shows a good dynamic behaviour. The experiment was also made for a sinusoidal reference signal and the results are shown in Figure 3b). Thereafter, the following experiment was made for the position control of the hydraulic press, and the results are shown in Figure 3c). Once these two control schemes had been proven separately, it was then merged together into a comprehensive structure in order to form a hybrid force/position-control strategy. This control structure allows independent force and position controllers to be used for the implementation of both control loops. In the force control loop a PID controller with an anti-windup algorithm is implemented, while the position control loop uses a PD controller. The controllers were tuned manually in order to achieve fast and smooth responses to the sinusoidal inputs in both the force and position control loop. The controller gains are set to the values: K_{pf} = 20, K_{if} = 2 and K_{df} = 0.5 for the force control loop and K_{px}=120 and K_{dx} = 0.1 for the position control loop. The force gain is set to the value of C_f=1.7 and the position gain is set to the value of C_p=1.2, and they determine the contribution of the control signal

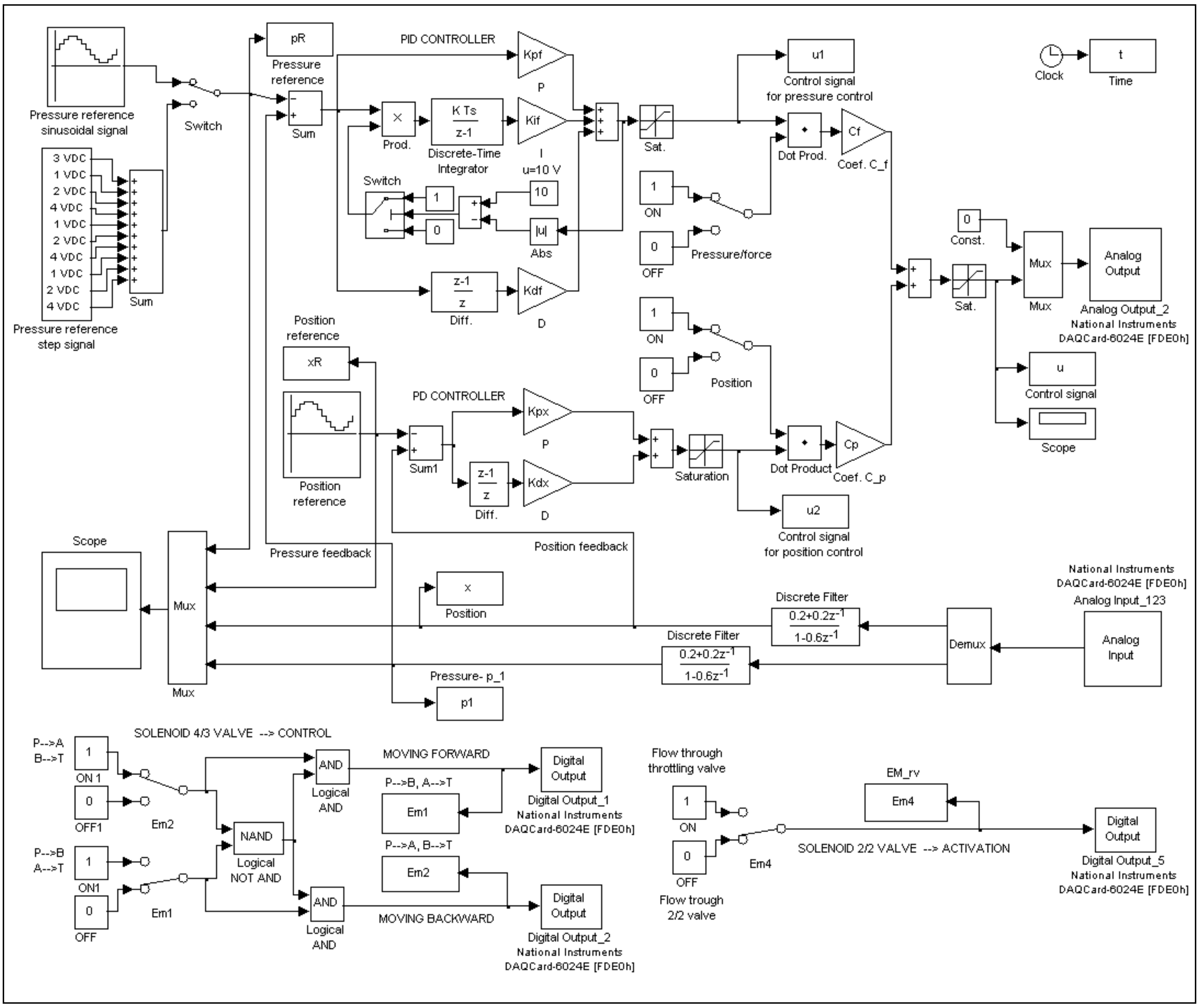

Figure 4. *Simulink model for hybrid force/position control*

applied to the servo valve. In Figure 3d) the experimental results of the hybrid force/position control for a sinusoidal reference signal are shown.

The Simulink/Real Time Workshop (RTW) model used to perform the process control is shown in Figure 4. The host PC with the RTW tool generates an ANSI C code automatically and enables a 'hardware in the loop feature' that has an ability to execute the Simulink model in real-time using an interface data-acquisition (DAQ) card. In this way it is possible to use the DAQ inputs and outputs as sources and sinks in the Simulink model. By activating various switches in the developed program, it is possible to choose the appropriate operating mode, type of reference signal and form of data storage.

Experiments were also performed using a PLC SIMATIC S7-1200 as a control device. Most hydraulic presses used in industry working in an open-loop and are usually operated manually or by using a control device such as a PLC. Figure 5 shows the HMI (human machine interface) that was built using the WinCC flexible software tool for the hydraulic press control. Using the HMI is intuitive, with a graphic and textual display, trends and alarms and it can perform real-time control and monitoring of the process. The HMI has the ability to display the amount of achieved cylinder position and pressure. The reference pressure can be directly changed, and there is a graphical representation of the pressure changes over time. Below the graphical display of the pressure condition there is also an alarm table, which gives the operator some important states in the process.

5 Conclusion

The hydraulic circuit and instrumentation of the hydraulic press, the simplified modelling of the system for computer control, the design and implementation of the computer program for hybrid position/force control have been presented. The control program was made in Matlab/Simulink, while C code was generated using the Real-Time Workshop program, making possible the realization of digital control algorithms. The tuned controllers derived for the independent force and position schemes gave satisfactory results in terms of trajectory

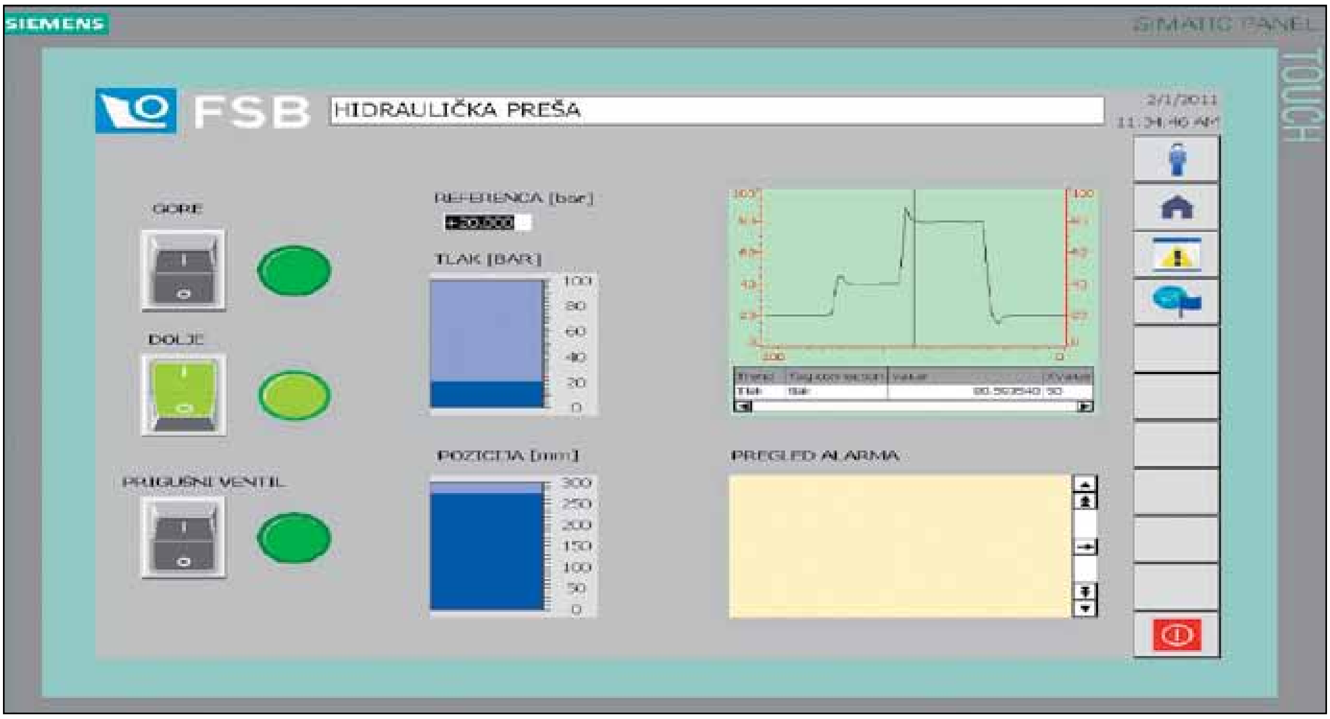

Figure 5. *HMI interface for the hydraulic press control*

tracking with an acceptable level of control error. Experiments were also performed using a PLC as a typical control device used in an industrial environment. Based on the experimental results it can be concluded that modern hydraulic presses offer good performance, efficiency and reliability; they are well adapted to different requirements of pressing, which is enabled by using modern microprocessor technology, new fast-acting valves and digital control theory.

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Regulacija sile in položaja na hidravlični stiskalnici

Razširjeni povzetek

V prispevku je prikazan postopek projektiranja in regulacije hidravlične stiskalnice (50 kN), izdelane tako za izobraževanje kot tudi za eksperimentalno verifikacijo krmilnih algoritmov. Za regulacijo delovnega tlaka v hidravličnem valju in posledično pritisne sile hidravlične stiskalnice služi tlačni servoventil. Stiskalnica za posredno merjenje pritisne sile je opremljena s tlačnim senzorjem, nameščenim direktno v komori hidravličnega valja. Stiskalnica omogoča tudi merjenje položaja batnice hidravličnega valja in posledično zgornje potisne plošče z uporabo mikropulznega merilnika pomika, kar je tudi pogoj za realizacijo hibridnega krmilnega algoritma (sila/položaj). Prispevek najprej prikazuje matematični model za hidravlično stiskalnico, upoštevaje dinamiko servoventila, kontinuiteto hidravličnih tokov skozi zožitve, tlačne spremembe v komorah hidravličnega valja ter drugi Newtonov zakon za gibajoče se dele stiskalnice. Na podlagi matematičnega modela je bil izdelan blokovni diagram krmilnega sistema (slika 1). Nato sta bili določeni še prenosni funkciji za hibridni (sila/pomik) krmilni sistem. Slika 2a prikazuje funkcijsko shemo, slika 2b pa fotografijo hidravlične stiskalnice. Glavni sestavni deli stiskalnice (sliki 2a in 2b) so: 1 – hidravlični valj, 2 – tlačni senzor, 3 – mikropulzni linearni merilnik pomika, 4 – elektromagnetni 4/3-potni ventil, 5 – servoventil, 6 – krogelni zapirni ventil, 7 – elektromagnetni 2/2-potni ventil, 8 – dušilni ventil, 9 – manometer, 10 – varnostni ventil, 11 – protipovratni ventil, 12 – tlačni filter, 13 – povratni filter, 14 – trifazni elektromotor, 15 – hidravlična črpalka, 16 – električna krmilna omarica, 17 – električni usmernik, 18 – programabilni logični krmilnik (PLC) SIMATIC S7-1200, uporabljen pri industrijski rešitvi krmiljenja in nadzora delovanja hidravlične stiskalnice, 19 – krmilno-nadzorni računalnik.

Krmilni algoritmi in nadzorni procesi se izvajajo istočasno, izvršeni so s pomočjo realnočasovne (ang. ''real-time'') računalniške opreme. Krmilni in nadzorni algoritmi so izdelani v programskem paketu Matlab/Simulink z uporabo orodij za istočasno (ang. ''real-time'') generiranje C-kode in izdelavo strojnega programa, ki krmili in nadzira delovanja hidravlične stiskalnice. Prispevek prikazuje tudi industrijsko rešitev krmiljenja hidravlične stiskalnice z uporabo programabilnega logičnega krmilnika (PLC) kot krmilne naprave.

V prispevku so najprej prikazani eksperimentalni rezultati regulacije sile preko krmiljenja in nadzora tlaka v hidravličnem valju. Največji problem teh meritev je, da sila trenja znotraj hidravličnega valja ostaja zunaj krmilne zanke. Uporaba povratne zanke za tlak v krmilno-nadzornem algoritmu nam omogoča krmiljenje izhodne sile stiskalnice. V prispevku predstavljeni rezultati meritev prikazujejo tlačne odzive na pravokotni (slika 3a) in sinusni (slika 3b) vhodni krmilni signal servoventila. Naslednji rezultati meritev (slika 3c) se nanašajo na odzive pomika batnice hidravličnega valja na sinusni vhodni krmilni signal servoventila. Zadnji predstavljeni rezultati meritev prikazujejo odzive hidravlične stiskalnice pri hibridnem krmiljenju (sila/pomik). Vsi predstavljeni rezultati kažejo na dobro dinamično odzivnost hidravlične stiskalnice in potrjujejo možnost uporabe v sodobnih industrijskih napravah. Slika 4 prikazuje blokovni diagram krmilno-nadzornega programa, izdelanega v programskem paketu Simulink za hibridno krmiljenje sile in položaja batnice hidravličnega valja stiskalnice. Preizkusi so bili najprej izvedeni s pomočjo krmilno-zajemne kartice DAQCard-6024E proizvajalca National Instruments. Nato so se vsi preizkusi izvedli še na krmilniku PLC SIMATIC S7-1200, izdelanem za industrijske namene. Slika 5 prikazuje vmesnik HMI (ang. human machine interface), ki je bil izdelan s pomočjo fleksibilnega programskega orodja WinCC in je namenjen za sodobno industrijsko krmiljenje in nadzor hidravlične stiskalnice.

Na osnovi eksperimentalnih rezultatov lahko zaključimo, da električno gnane sestavine, podprte z ustreznimi računalniškimi programi, omogočajo izboljšave delovnih karakteristik, izkoristkov in zanesljivosti hidravličnih sistemov, uporabljanih v sodobnih industrijskih proizvodnjah.

Ključne besede: hidravlična stiskalnica, regulacija sile in položaja, servoventil

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